Catheter-Based Mid-Infrared Reflectance and Reflectance Generated Absorption Spectroscopy

INVENTOR: HOI-YING N. HOLMAN

CROSS-REFERENCE TO RELATED APPLICATIONS:

[001]   This application relates to and claims priority to Provisional Patent

Application Ser. No. 60/529,073, filed on December 11, 2003, which is hereby incorporated

by reference in its entirety.

STATEMENT OF GOVERNMENTAL SUPPORT

[002]   This invention was made during work supported by U.S. Department of

Energy under Contract No. DE-AC03-76SF00098. The government has certain rights in this

invention.

BACKGROUND OF THE INVENTION

FIELD OF THE INVENTION

[003]   The present invention relates a reflectance-absorption spectroscopy method for

the *in vivo* characterization and imaging of chemical composition and molecular features in

abnormal tissues that are present in but are not limited to vascular diseases such as

atherosclerosis. Through the use of a broad-band photon source that emits light in the mid-

infrared (MIR) region, reflectance spectrographs and reflectance generated absorption

spectrographs of segments of normal tissues and tissues with chronic inflammatory conditions

were collected and compared. A number of MIR spectral bands were identified as diagnostic

markers for chronic inflammatory vascular conditions such as vulnerable plaques seen with

atherosclerotic disease. These markers were used to develop a catheter-based diagnostic

method and apparatus which use the broad-band MIR light or marker bands of MIR laser light

for detecting and imaging disease tissues, particularly vulnerable lesions and other vascular

diseases.

RELATED ART

[004]   Atherosclerosis is a common form of cardiovascular disease that leads to

insufficient blood supply to critical body organs, resulting in heart attack, stroke, and kidney

failure (Libby, P. *Scientific American* 2002, *286*, 47-55). Atherosclerosis can also cause major

complications in those suffering from hypertension and diabetes, as well as tobacco smokers.

It is known that this form of the cardiovascular disease is the leading cause of death and

disability in the developed world. In the United States alone, atherosclerosis is responsible for

almost one million fatalities each year, which is more than one half of all deaths. In addition,

almost 5 million persons are afflicted with cardiovascular disease and require hospitalization

for corrective surgery each year. Among those receiving corrective surgery, almost one half

would suffer in less than six months the recurrence of stenosis (an accelerated form of

atherosclerosis or artery stricture) and even sudden cardiac deaths (Ross, R. *Nature* 1993, *362*,

801-809), particularly in young men (Naghavi, M.; Madjid, M.; Khan, M.R.; Mohammadi,

R.M.; Willerson, J.T.; Casscells, S.W. 2002, 30).

[005]   Such failure of coronary angiography in determining the clinical severity and

in predicting future recurrence of acute coronary syndromes in symptomatic patients has

driven scientists to develop new diagnostic methods for identifying vulnerable atherosclerotic

plaques. Among them are the following promising technologies: contrast enhanced and

intravascular magnetic resonance imaging (MRI), optical coherence tomography (OCT),

electron-beam computed tomography (EBCT), angioscopy, elastography, intravascular

ultrasound (IVUS), and fluorescence spectroscopy. With the exception of fluorescence

spectroscopy (to some extend), these new methods aim at plaque structure/morphology or

plaque activity/physiology; although there is overwhelming evidence that atherosclerotic

plaques are not merely an accumulation of fat in the arterial wall. Medical research conducted

(Chan, A.W.; Ross, J. *Clinical & Investigative Medicine - Medecine Clinique et*

Experimentale 1997, *20*, 320-326; Kaneko, E. et al., *Coronary Artery Disease* 2000, *11*, 599-

606; Forte, , A. et al., A. *Journal of Cellular Physiology* 2001, *186*, 307-313) and clinical

observations (Davies, M.J.; Thomas, T. *Philos Trans R Soc Lond Biol Sci* 1981, *294*, 225-229;

Walts, A.E.; Fishbein, M.C.; Sustaita, H.; Matgloff, J.M. *Circulation* 1982, *65*, 197-201; Falk,

E. *Br Heart J* 1983, *50*, 127-134) acquired in the past decade have revealed that

atherosclerosis is indeed not a simple fat buildup at the arterial wall. Instead, it is an ongoing

active disease caused by progressing atherosclerotic/vulnerable plaques, which are an evolving

active collection of different migrated, proliferated, infiltrated cells (mainly smooth muscle

cells and immune cells especially inflammatory macrophages), apoptotic/narcotic cells, along

with one or more immune-triggering agents such as oxidized LDL and even infectious agents.

[006]   The most critical information needed for the accurate determination the

clinical severity and reliable prediction of future recurrence of acute coronary syndromes in

symptomatic patients is the microanatomic characteristics of plaque composition. A more

promising *in vivo* diagnostic tool for preventive cardiology should be a method that enable an

accurate identification and characterization in coronary patients of the plaques that are

vulnerable to rupture in the future, i.e. "vulnerable plaque."

[007]   Others in the art have recently attempted to provide Raman-based devices and

techniques for diagnoses of tissues. Raman-based devices and techniques involve irradiating

the tissue with light in the visible or near-infrared (NIR) regions of the electromagnetic

spectrum, detecting light re-emitted (only about one per 10^7 incoming photons) by the tissue at

the same frequency, or within a range of frequencies on one or both sides of the irradiating

light, and determine the Raman shifted frequencies in the MIR region to diagnose the tissue's

chemical conditions. An apparatus for the spectroscopic diagnosis of tissue conditions is

described in Rava et al., in U.S. Patent No. 6,697,665, and is hereby incorporated by reference.

Richards-Kortum et al., in U.S. Patent No. 6,095,982, describe methods and apparatus for

detecting tissue abnormality through fluorescence or Raman spectroscopy after excitation of

tissues in NIR wavelengths, and is also hereby incorporated by reference. Gellermann et al., in

U.S. Patent No. 6,205,354, described method and apparatus for the determination of levels of

carotenoids and similar chemical compounds in biological tissue such as living skin.

[008]   Unlike the present invention, these Raman spectroscopy methods and

apparatus are less sensitive to biomolecules with polar bonds and functional groups, which can

be important during inflammation or in disease tissues. They also rely on the low intensity of

re-emitting light (about one per 10^7 incoming photons) by the tissues, and often suffer

interferences from background autofluorescence signals from tissues.

BRIEF SUMMARY OF THE INVENTION

[009]   The present invention relates to methods and apparatus that exploit the drastic

changes in the optical properties in tissues in the mid-infrared region of the electromagnetic

spectrum because of the pathophysiologically induced changes in the chemistry and structures

of tissues. The invention comprises an optical method of detecting pathogenesis in tissues, and

of characterizing the pathophysiologic molecular and structural features of disease states

within vascular systems or other body compartments using mid-infrared (MIR) reflectance and

reflectance generated absorption spectroscopy. The pathophysiologic features of disease states

in tissues can be observed by increases in reflectance and in the numbers of reflectance

generated absorbance peaks in the range of wavenumbers 4000 to 400 cm^{-1}.

[010]   In one embodiment, the present invention involves first using a broad-band

photon source that emits light in the mid-infrared (MIR) region and collecting reflectance

spectrographs and reflectance generated absorption spectrographs of segments of normal

tissues and tissues with chronic inflammatory conditions. Exemplary MIR spectral bands are

herein identified and verified as diagnostic markers for chronic inflammatory vascular

conditions such as vulnerable plaques which are associated with atherosclerotic disease. Many

disease tissues contain reflective constitutents that absorb only part of the incident MIR light.

Light that is bounced off by reflective constituents inside the tissue is collected and amplified

and delivered to the computer for analysis. Reflected light measured at predetermined

wavenumbers or bands of wavenumbers are used to generate a spectral signal pattern

representative of the tissue conditions at the location of examination. Certain wavenumber

regions are shown to be informative in characterizing the state of the pathophysiology of

human disease and disorders including but not limited to atherosclerotic disease.

[011]   One object of the invention is to provide non-destructive *in vivo* devices,

methods and procedures for identifying and characterizing normal and diseased tissues using

mid-infrared reflectance spectroscopy and reflectance generated absorption spectroscopy.

[012]   Another object of the invention is to describe methods for measuring

reflectance spectra and for identifying reflectance generated absorption spectral markers in *in*

vivo tissues which are indicative of vascular, atherosclerotic or other diseases. Such

physiologically derived spectral markers that are indicative of the presence of, and not limited

to non-native or increased lipids, apoptotic or necrotic cells in a tissue, biomineralization (e.g.,

calcified deposits), infracted tissues, vulnerable plaques (VP), or inflammatory conditions.

One object of the invention is to provide methods and applications to diagnose or detect

coronary atherosclerotic heart disease.

[013]   The invention provides a catheter-based method of characterizing conditions

in a tissue, comprising (a) providing light in selected wavenumbers within the range of mid-IR

spectrum; (b) directing the light to an area of tissue at a location; (c)collecting light reflected

from the location and generating a reflectance spectra; and (d) comparing said reflectance

spectra to a reference spectra of normal tissue, whereby a location having an increased number

of absorbance peaks at selected wavenumbers indicates a tissue containing a physiological

marker. The step of providing light comprises the use of a mid-infrared source and directing

the light into the blood vessel of a test subject. In a preferred embodiment, the light is

delivered to the blood vessel of a test subject via a catheter having an optical probe.

[014]   Increased numbers of absorbance peaks can be observed in reflectance spectra

and reflectance generated spectra is in the range of wavenumbers 4000 to 400 cm^{-1}. In some

embodiments, the increased numbers of absorbance peaks are within at least one range of mid-

infrared wavenumbers selected from the group of: ~3500-3000, ~3020-3000, ~2950-2800,

~1800-1450, ~1710-1760, ~1690-1610, ~1520-1500, ~1480-1450, ~1100-900 and ~900-400

cm^{-1}. In certain embodiments, the increased numbers of absorbance peaks are in the range

between ~3000-3100 cm^{-1} and between ~1710-1760 cm^{-1}. In a preferred embodiment, the

presence of said physiological marker in said tissue is an indicator of disease tissue.

[015]   The catheter-based method can further comprise the step of generating a

spatially resolved map of reflectance generated spectral signals from different locations within

a tissue or the blood vessel or aorta of the test subject.

[016]   The invention further provides an apparatus for characterizing tissue

conditions, comprising: (a) a single or multiple source of mid-IR light covering a range of

mid-infrared wavenumbers; (b) a catheter coupled to said source and a detector or an array of

detectors to detect light reflected by a tissue; and (c) a computer means for generating the

reflectance generated spectra at selected wavenumbers detected by said detectors.

[017]   In one embodiment, the computer means has stored therein the reference

wavenumber range of 4000-400 cm^{-1}. In a preferred embodiment, the computer means has

stored therein the following reference wavenumber ranges, expressed in cm^{-1}: ~4000-2800,

~3500-3000, ~3020-3000, ~2950-2800, ~1760-1710, ~1690-1610, ~1520-1500, ~1480-1450,

and ~1100-900 and ~900-400.

[018]   In another embodiment, the catheter comprises a source fiber and a detection

fiber having a tip or tip array. The catheter can be inserted into the lumen of a patient's blood

vessel, artery or other tissues suspected of containing physiological markers indicative of

vascular disease or other inflammatory conditions.

[019]   In some embodiments, the apparatus can optionally comprise an

interferometer. In another embodiment, the apparatus can be further comprised of a tuning

system for the source, a cooling means for the detector, or the additional use of customized

bandwidth and special gain for DC- and/or AC-coupled preamps for the detectors to increase

the signal-to-noise ratio of the detectors.

[020]   The invention also provides a method of characterizing atherosclerotic plaque

of blood vessels, comprising the steps of: (a) providing light in selected mid-IR wavenumbers

between about 3800 to about 2800 cm^{-1} ; (b) directing the light through a probe to an area on a

blood vessel or aorta; (c) measuring reflected light returning through the probe over a range of

said wavenumbers to generate a pattern of spectral signals representative of said area; and (d)

comparing spectral signals from a reference spectra to the spectral signals from said area,

whereby an having atherosclerotic plaque has enhanced reflectance and increased spectral

features.

[021]   The invention also provides a method of characterizing a biological material

that has enhanced reflectance and/or spectral features, comprising the steps of: (a) providing

light in selected mid-IR wavenumbers between about 4000 to about 400 cm^{-1}; (b) directing the

light through a probe to an area of said biological material; (c) measuring reflected light

returning through the probe over a range of said wavenumbers to generate a pattern of spectral

signals representative of said area; and (d) comparing spectral signals from a reference spectra

to the spectral signals from said area for enhanced reflectance and/or spectral features.

[022]   In one embodiment, light is provided in mid-IR wavenumbers between about

3800 to about 2800 cm^{-1}, whereby an area of the biological material having enhanced

reflectance and increased spectral features is indicative of an atherosclerotic plaque.

[023]   In another embodiment, light is provided in at least one range of selected mid-

IR wavenumbers selected from the group of: ~3020-2800 cm^{-1}, ~1760-1710 cm^{-1}, ~1450-1460

cm^{-1}, and ~1200-900 cm^{-1}, whereby an area of the biological material having enhanced

reflectance and increased spectral features is indicative of the presence of non-native lipids.

[024]   In another embodiment, light is provided in at least one range of selected mid-

IR wavenumbers selected from the group of ~1740-1400, ~1100-900 and ~900-400 cm^{-1},

whereby an area of the biological material having enhanced reflectance and increased spectral

features is indicative of inflammatory conditions.

[025]   In another embodiment, light is provided at selected mid-IR wavenumbers

between about 1740-1700 cm^{-1}, whereby an area of said biological material having enhanced

reflectance and increased spectral peaks are indicative of increased numbers of leukocytes,

lymphocytes and macrophages.

[026]   In another embodiment, light is provided selected mid-IR wavenumbers are

between about 1100-900 cm^{-1}, wherein enhanced reflectance and increased spectral peaks at

about 1090, 1052, or 965 are indicative of lymphocytes and macrophages thereby indicating

an inflammatory condition of accumulations of leukocytes, specifically lymphocytes and

macrophages. In yet another embodiment, all three ranges of selected mid-IR wavenumbers is

provided and measured.

[027]   In another embodiment, light is provided at selected mid-IR wavenumbers

between about ~1690-1610 cm^{-1}, whereby an area of said biological material having enhanced

reflectance and increased spectral peaks at ~1620 cm^{-1} and ~1678 cm^{-1} is indicative of accumulation of dead (apoptotic and/or necrotic) cells in a tissue.

[028]   In another embodiment, the invention provides for a method of spectroscopic diagnosis of tissue comprising: (a) irradiating a subsurface portion of tissue at a target area with radiation having a frequency within the mid-infrared range, transmitted through a fiber optic cable; (b) detecting light reflected by the area of tissue in response to the radiation, the light having a range of 4000 cm^{-1} to 400 cm^{-1}; and (c) analyzing the detected reflectance light to diagnose the tissue including the step of comparing the detected light with reference data.

[029]   In one embodiment, in the detection step the reflected light is collected through the fiber optic cable. In another embodiment, in the irradiation step a catheter means is provided for insertion of the fiber optic cable in body lumens. The fiber optic cable receives light reflected by the tissue and transmits the reflected light to a spectroscopic analysis system. In another embodiment, an alternate spectrophotometer can be used to receive the reflected light. In another embodiment, the method can further comprise a step of rotating the fiber optic cable radially within the body lumens, whereby data is acquired at various target locations radially within the lumen. The step of radial acquisition of data can be repeated thereby performing a 360-degree spectral analysis of the body lumens.

[030]   In another embodiment, a method of characterizing conditions in a tissue, comprising the steps of: delivering mid-infrared bright light to a tissue to be diagnosed, irradiating said tissue with said bright light, detecting light reflected by the tissue within the same range of MIR frequencies, and determining the chemical composition and cellular conditions in the tissue.

BRIEF DESCRIPTION OF THE DRAWINGS

[031]   FIG. 1A is a schematic showing one embodiment for a system to measure the MIR reflectance generated spectra of a tissue suspected of having lesions or diseased portions. FIG. 1B is a diagrammatic illustration of one embodiment of a catheter-based system to be deployed in an artery or a body compartment of a test subject; note that the FTIR interferometer may or may not be needed. FIG. 1C is a schematic showing the distal end of the catheter inserted into the lumen of a vessel.

[032]   FIG. 2 is a graph demonstrating the motivation of using a bright and coherent light source instead of the conventional thermal source. The signal-to-noise ratios (SNR) increase significantly with the use of a bright source.

[033]   FIG 3. compares reflectance spectrographs of aorta tissue (a,b) having vulnerable plaques and (c,d) without vulnerable plaques.

[034]   FIG 4. summarizes reflectance generated absorption spectrographs showing data from (a) an aorta tissue free of VP, (b) an aorta tissue of VP , (c) a non-atherosclerotic tissue with lipids droplets, and (d) macrophages in an abscess of non-atherosclerotic tissues.

[035]   FIGs. 5A-5B are visible micrograph of a section of the aorta from an ApoE (-/-) mouse that has atherosclerotic plaques. Numbers on the micrograph in FIG. 5B indicate the locations of measurements. (The corresponding MIR reflectance generated absorption spectra measured at these sampling locations are shown in FIGs 6-8, which demonstrate in details the uniqueness of the spectral fingerprints for vulnerable plaques.)

[036]   FIG. 6A-6B presents reflectance and reflectance generated absorption spectrographs from sampling points 12 and 13 as depicted in FIG 5B, which are in an area being free of atherosclerotic plaque.

[037]   FIG. 7 presents reflectance generated absorption spectrographs for locations 4, 2, 6, and 7 as depicted in FIG. 5B, an area of the aorta with vulnerable atherosclerotic plaque.

[038]   FIG. 8 presents a reflectance generated absorption spectrograph for locations 8, 9, 10 and 11 of FIG. 5B, an area of the aorta also with vulnerable atherosclerotic plaque.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

INTRODUCTION AND METHODS

[039]   The present invention relates to methods and systems of performing reflective MIR spectroscopic diagnosis of disease tissues. The presence of highly reflective crystalline and other fine-structure components in disease tissues, and the fact that many of these non-native materials contain very little water, have provided an opportunity to use the sensitive MIR reflectance and reflectance generated absorption spectroscopy to probe

pathophysiological conditions in tissues *in vivo*. Unlike normal tissues that usually attenuate a large fraction, or even all of incoming MIR light, many constituents inside disease tissues including but not limited to atherosclerotic tissues are effective MIR reflectors that can transform the tissue into a highly reflective matrix. By analyzing the reflectance generated absorption spectral bands, one can readily characterize the conditions of the tissues. For atherosclerotic tissues, for example, the targets are the presence of unusual amount of lipids, cholesterol crystalline, calcified deposits, foam cells, apoptotic or necrotic cells, collagen, and nitrated protein.

[040]   The present invention utilizes in part MIR reflectance spectrographic technology in conjunction with MIR sources that are brighter than the conventional thermal MIR sources. The advantages of MIR spectrographic technology as described herein are: (1) MIR has minimum scattering and autofluorescence in biological samples; (2) MIR spectroscopy can provide a wealth of information that is molecule and structure specific (e.g., providing inherent chemical information about functional groups, including their types, interactions and orientation) with high sensitivity; (3) MIR spectroscopy can identify physiological states of cells (e.g., foam cells, blood cells, cells at different cell cycles, dying cells); and (4) it can be a qualitative and quantitative technique without the use of dyes or labeling chemicals. The advantages of a bright light source, especially those that can act as a coherent light source, are that it can penetrate deeper into biological tissues and biological fluid such as blood, and that it can increase signal-to-noise ratios in the MIR reflectance spectral measurements at individual cells as well as individual plaques.

Mid-Infrared Reflectance Generated Absorption Spectroscopy of Tissue Lesions

[041]   Biomineralization results in formation of non-native materials such as microcalcification, which is commonly found in disease tissues, such as benign and malignant lesions of breast tissues and atherosclerotic tissues. Non-native materials found in these disease tissues have very little water and are highly reflective to MIR light. Their presence in tissues converts the tissues into a MIR reflective matrix, thus providing an opportunity to use MIR reflectance and reflectance generated absorption spectroscopy to sensitively probe pathophysiological conditions in tissues. The tissues can be examined *ex situ, ex vivo, in vivo*.

[042]   FIG. 1A schematically illustrates a preferred embodiment of the device **100** to

measure the MIR reflectance generated spectra of a tissue suspected of having lesions or

diseased portions. In one embodiment, a device as described and shown in Hoi-Ying N.

Holman, Michael C. Martin, and Wayne R. McKinney, "Tracking chemical changes in a live

cell: Biomedical Applications of SR-FTIR Spectromicroscopy," *Proceedings of the First*

International Conference on Biomedical Spectroscopy, Cardiff, Wales, July 7-10, 2002.

Spectroscopy - An International Journal **17**(2-3), 139-159 (2003). LBNL-51337, can be used.

Generally the device **100** comprises a mid-IR light source **110**, a detector **120** connected to a

computer means **130**. The IR light source **110** also can be optically connected to an optional

diffusive reflectance spectroscopy interferometer or a Fourier transform infrared (FTIR) bench

with a Michelson interferometer **112**. The source **110** emits mid-infrared light **130** at the loci

of the tissue sample spot **140** to be interrogated. The arrows in the schematic show the

direction of the light **140**. The detector **120** detects the reflectance generated light after it has

been reflected and absorbed by the tissue sample **140** and transmits the signal to the computer

means **190**.

[043]   A computer or other means **190** stores the spectral information which is a

spectrograph of light intensity versus wavenumber or wavelength. This spectral information

can be displayed immediately on an output display means **195**, compared with reference

spectra stored in the computer, displayed on the differential spectral display **198** and analyzed.

Such analysis and comparison will provide a quantitative image of the distribution of lesions

in the tissue. The computer **190** may have stored therein spectral characteristics of the mid-

infrared reference wavenumber segments expressed in units of cm^{-1}. Having stored spectral

characteristics in these segments and reference numbers allows the device to generate a pre-

interpreted output.

[044]   Analysis and interpretation of MIR reflectance generated absorption

spectroscopy of tissues involves measuring the reflectance of incident MIR radiation as a

function of photon energy, and mathematically converting to absorbance as a function of

photon energy. Mid-infrared radiation is in the region of the electromagnetic spectrum which

is bound by the near infrared (NIR) region at high frequencies and the far infrared (FIR)

region at low frequencies. The present technique focuses on the application of reflectance from tissues of molecular and structural features from the MIR region of the electromagnetic spectrum because of its wealth of chemical information with exceedingly high sensitivity.

[045]   The energy (E) of MIR photons may range from 0.5 to 0.05 eV, or in terms of wavelengths (λ) from 2.5 to 25 μm, or the wavenumbers (v) range from roughly 4000 to 400 cm^{-1}. At present, a wavenumber defines the number of waves per unit length. The term, "wavenumber" is used herein to mean $1/\lambda$ where λ is the wavelength. Wavenumbers and wavelengths can be inter-converted using the following equation:

$$v \text{ (in } cm^{-1}) = (1 \times 10^4) / \lambda \text{ (in } \mu m) \qquad (I)$$

[046]   Wavenumbers and energy can also be inter-converted using the following equation:

$$v \text{ (in } cm^{-1}) \sim 8100 \times E \text{ (in eV)} \qquad (II)$$

[047]   Thus, wavenumbers are directly proportional to the energy associated with the photon, and inversely proportional to the wavelength. The wavenumber unit (cm^{-1}, reciprocal centimeter) is more commonly used in modern infrared instruments that are linear in the cm^{-1} scale. At present, the recommended unit of wavelength is μm micrometers, but μ (micron) is used in some older literature.

[048]   When MIR photons enter healthy tissues, most photons are attenuated inside the tissue and very little are reflected. However, when MIR photons enter disease tissues such as atherosclerotic or inflammatory tissues, some MIR photons are "reflected" or in other words, bounced off and redirected by non-native constituents inside the disease tissue. Thus, the term "reflectance" as used herein, is meant the measurement of the photons reflected and redirected by non-native constituents in a tissue. The photons can then measured at each mid-infrared wavelength. By defining "reflectance" as used herein, R, as the ratio of the detected light intensity I to the incident light intensity I_o, one can express reflectance (R) in terms of absorbance (A) as the logarithm to the base 10 of the reciprocal of the reflectance (R).

$$A = \log_{10}(1/R) = -\log_{10}R = -\log_{10}(I/I_o) \qquad (III)$$

[049]   This equation holds for each single wavenumber through out the entire MIR

spectrum. By measuring the reflectance of mid-infrared photons over a series of wavelengths,

it is possible to obtain absorption information via equation (III). Infrared absorption occurs

only when the frequency of the incident infrared photon matches exactly the molecular

vibration frequency which produces an oscillating dipole moment perpendicular to the plane

of incident. This selective absorption makes infrared spectroscopy a powerful means of

studying the composition and structure of biological samples.

[050]   The data transformation process described above allows one to compare the

band characteristics of a reflectance generated absorption spectrum with those in a MIR

absorption database, such as those available in the art. This comparison provides an

opportunity to identify and measure the presence of a certain function group or even a certain

type of biomolecules found in a disease tissue.

[051]   In one embodiment, data is displayed both in the form of reflectance and of

reflectance generated absorbance. Infrared absorption information is generally presented in the

form of a spectrum with wavenumber or wavelength as the x-axis, and percent reflectance or

absorbance as the y-axis. Reflectance spectra provide better contrast between intensities of

strong and weak bands because reflectance ranges from 0 to 100% whereas absorbance ranges

from infinity to zero. The same sample will give quite different profiles for the infrared

spectrum, which is linear in a wavenumber. It will appear as if some infrared bands have been

contracted or expanded.

[052]   In studying spectra of disease tissues, one may notice from spectral peak shape

that MIR reflection measured may be a combination of specular reflection and diffusion

reflection, depending on the incident angle(s) of the beam and the local surface roughness of

the tissue in comparison to the wavelength of the MIR photons. Issues of specular reflectance

can be addressed in various ways, including by varying the angles of incidence, by applying

Kramers-Kronig transformation to pre-process the reflectance data, or by building a spectral

library of specular reflection of tissues. Such a library will enable the identification of the

presence of specular reflection, accelerating data processing and analysis.

[053]   Absorption spectra are obtained from reflectance measurements via equation (III), which may be incorporated in software or algorithms used on the computer means 190 for analysis. While looking at tissues with plaques, one may notice from spectral peak shape that MIR reflection in a certain range of wavenumbers may be dominated by specular reflection or a combination of specular and diffusion reflection. Specular reflectance spectra possess derivative-shape bands, and are distinctly different from diffusion reflection spectra. To process the reflectance data in the spectral region wherein specular reflection dominates, processes such as Kramers-Kronig transformation can be used. A spectral library of specular reflection of aorta tissues of different disease states also can be built to help accelerating the data processing and analysis. The final outputs are spectra that are often closed to the conventional absorption spectra.

[054]   Analysis of reflectance generated absorption spectra can be further carried out by observing the spectral features, changes and characteristics (e.g., peak position, peak height, bandwidth) of multiple bands within defined wavenumber regions or "marker segments" on spectrographs such as those shown in the boxed regions in the FIG 4. By observing spectral features in these marker segments in the MIR region, the presence of various physiological markers and features can be detected, including the presence, absence or changes in specific types of tissues, cells, proteins, lipid compositions and structures, biomineralization, or other biomolecules. By the term, "spectral features" it is intended to include features such as unique peaks, single or multiple peaks, broad peaks and envelopes that are typically observed in spectroscopy, and is used interchangeably with descriptions of such features.

[055]   According to the method, physiological markers can be identified by unique MIR features within MIR marker segments to indicate the presence of absence of plaques prone to rupture (i.e. vulnerable plaque). No dyes, contrasting agents, or labeling compounds are necessary for the reflectance measurements to differentiate tissues with plaques from tissues that are free of plaques. The unique composition and structure associated with vulnerable plaques (VP) have made VP a natural amplifier for diagnosing atherosclerosis by means of reflective absorption spectroscopy.

[056]   Furthermore, the present method can detect the presence of physiological

atherosclerotic markers such as LDL, oxidized LDL, foam cells, infiltrated inflammatory cells,

biomineralization, and excessive cell death such as apoptotic/necrotic cells. As shown in FIGS

3 and 4, the present method can also detect markers and features of apoptotic and necrotic

cells, including but not limited to, activated macrophages, inflamed macrophages, and foam

cells; the presence of nitrated protein; biomineralization; changes in the nature of lipid

compositions and structures, such as cholesterols, high density lipids (HDL), low density

lipids (LDL) and oxidized low density lipids (oxLDL); the presence of infarcted tissues

(modification of the extracellular matrix following myocardial infarction;

denatured/aggregated proteins) and normal aortic tissue; and other physiological markers

correlated with plaques prone to rupture (i.e. vulnerable plaques).

[057]   Using the method to study sites of inflammation, one can also observe

increased numbers of absorbance peaks is in the range of wavenumbers 4000 to 400 cm^{-1}.

Specfic wavenumber regions and ranges can be selected to interrogate a tissues. For example,

different spectral features may arise in marker segments between wavenumbers 3500 and 2800

and between 1800 and 900 cm^{-1}, a smaller range of wavenumbers can be "selected" to

interrogate a tissue. In certain embodiments, spectral features were found to be observed at

the following reference wavenumber segments expressed in units of cm^{-1}: 4000-800, 3800-

2800, 3050-2800, 1800-1000, 1760-1710, 1700-1610, 1600-1500, 1520-1500, 1480-1450,

1100-900 and 900-800 cm^{-1}.

[058]   The following marker segments are exemplary of the types of marker

segments that can be characterized by the unique peaks or spectral features associated with

those from disease tissues as compared to reference spectra from normal tissues. These unique

MIR reflectance generated absorbance peaks in the spectral tracing generally correspond well

with those obtained from MIR transmittance generated absorbance peaks that are indicative of

excised specimens having vulnerable plaques. Reflective absorption spectral peaks observed at

these wavenumbers may be associated with relevant chemical or biological conditions

associated with a blood vessel as described herein and summarized in Table 1 below.

Table 1. Examples of MIR reflectance generated absorption markers for characterization and/or identification of vulnerable plaques. These markers were obtained by using the apparatus and method described in this invention

Approximate Band position in cm^{-1}	Assignment	Associated features in vulnerable plaques
~ 3800 - 3000 (centered at ~3300)	Hydroxyl peaks [νOH stretching]	Features: A decrease in absorption intensity in this region. Causes: Structural proteins (e.g., elastin) in the arterial wall are prone to calcification during the process of atherosclerosis. Protein calcification is known to involve a significant lost of hydroxyl content because of the participation of the hydroxyl group of proteins in calcium coordination to form aggregated species (Vyavahare et al. 1999).
~ 3005	Stretching vibration of an olefinic=CH band of unsaturated lipid chains of cellular lipids including phosphatidylserines at the outer plasma membrane leaflet.	Features: The absorption intensity at ~ 3010 will increase. Causes: Atherosclerotic plaques have excess apoptotic cells which are known to increase their production in phosphatidylserines and the presence of externalized phosphatidylserines.
~ 2950, ~ 2870	Asymmetric and symmetric stretching vibration of CH$_3$ groups	Features: A decrease (relative to the absorption intensity for CH$_2$ groups) in absorption intensity. Causes: Vulnerable plaques are associated with high contents of collagen which has

		limited number of methyl containing side-chains.
~2926, ~ 2852	Asymmetric and symmetric stretching vibration of the lipid acyl CH_2 groups of fatty acids	Features: A drastic increase in absorption intensity. Causes: Vulnerable plaques have high contents of non-native lipids with large numbers of CH_2 groups.
~1750 - 1720	Stretching vibration of the lipid ester carbonyl (C=O) groups. The exact location depends on the local hydrogen-bonding environment with shifts of approximately 50 cm^{-1}. For example, the lipid C=O groups that are not hydrogen-bonded and do not interact with hydrogen bond donors, the peak positions tend to center at higher frequencies. Vibration peaks associated with hydrogen-bonded lipid C=O groups tend to center at lower frequencies.	Features: A very intense sharp peak arises from non-native lipids. The peak parameters can be used to determine the lipid constituents, morphology, and mobility in the plaque. Cause: High-content of non-native phospholipids and cholesterol esters with C=O groups exceedingly sensitive to the immediate hydrogen bonding environments in surrounding cellular/tissue environments. ~ 1747-1743: the lipid C=O groups are in a highly non-polar immediate environment (e.g., non-polar fatty acids); highly immobile. ~ 1740: Stretching of C=O groups for lipids with some polar constituents such as phosphates, sugar and amino groups. ~ 1735: Stretching of phospholipid C=O groups for simple lipids such as cholesterol esters; C=O groups are more hydrogen-bonded; mobile. ~ 1723: C=O groups in protonated environments
~1690 - 1610	Arising from C=O stretching of the	Features: New peaks at ~ 1678, but mostly 1620.

	peptide groups of proteins (Amide I). 1678, 1620: Aggregated or denatured proteins (dead cells) 1659, 1637: α-helix/β-sheet	Causes: Protein aggregations are known to associate with myocardial infarction (cell death) found in vulnerable plaques.
~1560 - 1520	Arising from N—H bending vibration of the peptide groups of proteins (Amide II). Highly sensitive to the local environment of H in the N—H groups. Strong hydrogen bonds restrict the bending vibration and increasing the frequency.	Ratio of absorption intensity of Amide I to Amide II for red blood cells are similar to pure proteins (Chiriboga et al. 1998)
~ 1515	Tyrosine ring vibration band: Tyr—OH, v(CC), σ(CH)	Nitrotyrosine → 1510; nitrotyrosine is generally associated with nitrated proteins, and is often found in vulnerable plaques.
~ 1467	Bending vibrations of the lipid acyl CH_2 groups	Features: Become very prominently strong and sharp peak(s) in vulnerable plaques Cause: Abundance of acyl CH_2 groups in non-native phospholipids and cholesterols.
~1200-900	Phosphate vibration region	Features: Become distinctive with mineralized tissues
~1090, ~1052, ~ 965	Vibrations of the P-O and C-O groups of the	Features: Pronounced peak for glycogen-poor cells such as lymphocytes and macrophages

	sugar-phosphate backbone of DNA	Causes: Vulnerable plaques have abundance of macrophages

[059]   All wavenumber regions and specific wavenumbers described herein and also

presented in Table 1 are approximate, and are meant to include ± 15 wavenumbers. This is

also further indicated by the terms, "about" and "approximate" and by the symbol, "~", which

are meant to indicate that the wavenumbers should include ± 15 wavenumbers from the

indicated wavenumber or wavenumber range.

[060]   FIG 3. compares reflectance spectrographs of aorta tissue (a, b) with

vulnerable plaques and (c, d) without vulnerable plaques. The spectrograph shows that normal

aorta tissues hardly reflect the MIR photons and form a "silent" background spectrum either

throughout the MIR region (trace c) or in the region of wavenumber 3600-2800 cm^{-1} and the

region of wavenumber 1800-1000 cm^{-1} (trace d). However, in atherosclerotic tissues, detailed

sharp peaks and features appear in these two spectral regions (trace a, b).

[061]   FIG 4. illustrates a typical reflectance spectrum dominated by specular

reflectance in the tissue of an atherosclerotic aorta. Shown are the traces for aorta tissue

without vulnerable plaque; vulnerable plaques (lipid droplets, macrophages and apoptotic

cells); lipid droplets on non-atherosclerotic tissue; inflamed macrophages in abscess of non-

atherosclerotic tissues. Shown are boxed regions are marker segments where spectral features

indicative of disease tissues containing non-native constituents can be found. The peaks

pointed to by arrows indicate the types, kinds and unique peaks that can be found within these

marker segments of disease tissues containing non-native constituents.

[062]   FIG. 5 is a summary graph of the MIR spectra of tissues of different

inflammation conditions detected by the present method and apparatus and the different

results that may be obtained. The Figure shows a spectrogram plotting wavenumber versus

absorbance (as measured by reflectance generated absorption spectroscopy). Reflectance

generated absorption spectra that have very broad and featureless "background absorption" are

typical of normal aorta tissue observed in areas free of plaques.

[063] Additional absorption peaks are seen in tissues with vulnerable plaque. In one embodiment, these peaks are generally in the region of wavenumbers 3100-2800 cm^{-1}, 1800-1700 cm^{-1} (an area related to C=O groups) and 1600-1500 cm^{-1}, which arise from the vibrations of the lipid acyl –CH_2 groups, C=O stretching and from the N—H bending of the peptide groups in proteins and in other areas, such as ~1467 and ~1090 cm^{-1}, ~1050 cm^{-1}, and ~968 cm^{-1}, which may be assigned to the bending (scissoring) vibrations of the lipid acyl – CH_2 groups, and the C-C/C-O stretching vibration characteristics of the deoxyribose sugar moiety connected to phosphates in DNA. The locations of infrared absorption peaks of protein Amide I at ~1680 cm^{-1} and ~1620 cm^{-1} may arise from the presence of protein aggregations that are known to associate with myocardial infarction (cell death) found in vulnerable plaques.

[064] In general, the fine fingerprints centered at approximately 2950 cm^{-1} in the 3020-2800 cm^{-1} region are considered highly diagnostic for vulnerable plaque, in that they are associated with the presence of numerous apoptotic cells (for example, a peak at ~3005 cm^{-1}, which is associated with the increasing production in phosphatidylserines and the presence of externalized phosphatidylserines) in addition to increases in collagen contents and non-native lipid pools having peak characteristics at ~ 2950, ~2926, ~2870, and ~2852 cm^{-1}.

[065] Also, peaks arising from C=O groups at approximately 1760-1710 are highly significant in that the peak location and fine structure are very good indicators of the mobility, structure, and polarity of lipids as well as the protonated environment of the cells or tissues which are not found in normal or non-inflamed plaque.

Intravascular MIR Reflectance Generated Absorption Spectroscopy

[066] In another embodiment, a non-destructive *in vivo* diagnostic method and procedure is provided for intravascular MIR (IMIR) reflectance and reflectance generated absorption spectroscopy.

[067] In one embodiment, this method is used to diagnose atherosclerosis *in vivo*. Contrary to healthy tissues, atherosclerotic tissues contain non-native constituents including lipid droplets, cholesterol crystals and clefts, calcium hdyroxyapatite crystallines, foam cells. They have very little water, and at the same are known effective MIR reflectors. A fraction of

the light that enters the atherosclerotic tissue bounces around beneath the tissue surface, is re-directed and leaves the tissue. This reflected light will be collected and analyzed for chemical composition and cellular conditions of the tissue.

[068]   The analysis of the IMIR reflectance spectra of the present method involves the identification of at least two different spectra: the generally non-descript features of normal aorta tissues without atherosclerotic plaques viewed over a continuum of MIR wavelengths, and the specific features of aortic atherosclerotic plaques (FIG. 3). The term "continuum" is considered herein as the "background reflectance generated absorption spectra" of normal tissues. The specific reflection generated absorption spectral markers are those that are correlated to the physiological, chemical and structural conditions of inflammation and modification of cellular matrix being studied. The specific reflectance generated absorption spectral features are superimposed onto the continuum.

[069]   In one embodiment, the present invention can be used to diagnose atherosclerosis in a living subject by means of a catheter passing through the subject's artery. A catheter-based diagnosis system in a preferred embodiment is illustrated in FIG. 1B and described below. Through the use of a catheter, a cardiovascular plaque can be subjected to comparative MIR reflectance generated absorption spectral analyses.

[070]   Referring to FIG. 1C, the light carrying catheter is introduced into the artery or tissue to be studied. A bright MIR light is delivered to the tissue to be interrogated through a source fiber. The light source can generate readings to a depth of up to hundreds of microns. The distal end of the catheter should be placed adjacent to or in contact with the arterial and vascular interrogation sites in the vessel or tissue. In FIG. 1C, an artery is illustrated, and the catheter is shown in physical contact with the surface of that artery. As is shown, the artery comprises several layers of muscle and epithelial tissue, and may or may not contain areas of plaque. Vulnerable plaques can usually be found within the first tens of microns below the tissue surface (tunica intima).

[071]   An *in vivo* sample studied by the IMIR spectroscopy method described herein is typically comprised of tissues suspected of having inflammatory cells, lipid pools and other immune triggering agents such as oxidized low density lipoproteins (OxLDL), cells that

mediate an inflammatory/immune response, such as leukocytes, specifically macrophages or individual lesions. The lesions that can be studied include, but are not limited to, macrophages and/or lipids that are part of non-atherosclerotic inflammation (e.g., abscess) or atherosclerotic plaques. The teachings of the present invention may also be adapted for applications to other disease states involving the study of a lesion or inflammation, cell death, apoptosis and/or necrosis.

[072]   The MIR diagnosis of atherosclerotic tissues is not problematic even beneath a layer of blood. For example, if the atherosclerotic tissue to be diagnosed is an artery, the presence of blood in the vessel should not diminish the ability to detect reflectance generated spectra.

[073]   In one embodiment, this can be accomplished by using a very bright infrared source such as a free electron laser or a coherent laser. In another embodiment, one can limit the thickness of blood between the cell surface and the measurement system by employing an intra-aortic balloon catheter having a tip detector or tip array. The balloon can be inflated at the location of measurement to minimize the thickness of blood between the cell surface and the measurement system. In addition, if the data acquisition moments are synchronized with the heartbeat of a patient, the effect of blood will be minimized further. As the blood vessel contracts with each heartbeat, data is taken at that moment because the vessel contracts more tightly around the tip array of the catheter. It is also contemplated that a pressure-sensor may be present in the tip array to synchronize data acquisition with each contraction.

[074]   The presence of red blood cells is being observed if the ratio of the peak area centered at about 1650 cm^{-1} to the peak area centered at 1545 cm^{-1} is similar to the ratio detected in protein. Specifically this indicates that the probe tip is detecting blood cells, rather than the blood vessel endothelium. Thus in embodiments where detection of tissue or the epithelium is desired, it is important to keep the probe tip in direct contact with the surface to be studied.

[075]   The present method also provides MIR images of atherosclerosis in blood vessels such as an aorta. In one embodiment, the reflectance spectra is measured and mapped at various points along the blood vessel. In another embodiment, reflectance data is acquired at

various points radially within a blood vessel, thereby performing a 360-degree spectral analysis.

[076]   It is contemplated that the present technique may optionally be used in conjunction with other known catheter-based diagnoses and treatments of cardiovascular diseases.

Apparatus and Experimental Set-up for IMIR

[077]   The present apparatus is built upon the experimental set up at the infrared beamline at the Advanced Light Source (ALS) at the Lawrence Berkeley National Laboratory, which may be adapted for a more commercial application, as described below and in the subsequent demonstration examples.

[078]   FIG. 1B illustrates a preferred embodiment for a catheter-based system using a broad-band light that provides photons with energy that span the entire mid-infrared region. The system includes the mid-infrared detection system **100** with broad-band light source **110**, detector **120** and a computer **190**, optionally connected to an interferometer **112**. The source fiber **150** and detector fiber **160** are coupled within a catheter **200** having the detector tip **180**. The light source **110** emits coherent MIR light, which is directed into an interferometer **112** to be modulated, and then passed to the catheter **200** that can be introduced into a subject. For example, the catheter **200** can be inserted through a vascular system to a body area for diagnosis. The modulated light that exits the interferometer **112** is delivered to a precise location via the optical fiber **150** inside the catheter **200**.

[079]   The light exits the source fiber **150** and enters the tissue. In one embodiment, the light enters the tissue at a specified incident angle chosen by varying the angles of an incidence selector. An appropriate selection of angle(s) of choice provides measurements that allows for the identification and separation of specular reflection during data analysis. In one embodiment, the catheter fiber optic system has the option to rotate 360° and thus provide a 360° spectroscopic viewing of a vessel such as aorta.

[080]   The present invention is particularly adapted for directly measuring MIR-light being reflected, rather than being absorbed or transmitted. Thus, absorbance is generated by analyses of the reflected light from the tissues. Normal tissues reflect very little of the MIR

light that penetrates the tissues. However, disease tissues such as atherosclerotic tissues contain highly reflective constituents. Light that enters the tissues is "bounced" around beneath the tissue surface by these reflective constituents and absorbed in part before redirected and leaving the tissue surface for collection. Referring to FIG. 1B, the direction of light is shown schematically by the arrows **130**. The reflected light returned to the detector fibers **160**, is amplified and detected by a detector or an array of detectors **120**.

[081]   A computer or other means **190** stores the spectral information which is a spectrograph of light intensity versus wavenumber or wavelength. In one embodiment, the computer **190** has software packages that can produce from this spectral information, reflectance spectra or reflectance generated absorption spectra at each location of interest the aorta. This spectral information can be displayed immediately on a output display means **195**, and compared with reference spectra stored in the computer and displayed on the differential spectral display **198**. Spatial displays of results from the comparison will provide a quantitative image of the distribution of lesions in the tissue.

[082]   The computer **190** may have stored therein spectral characteristics of the mid-infrared reference wavenumber segments expressed in units of cm^{-1}. Having stored spectral characteristics in specific wavenumber segments and reference numbers allows the computer **190** to generate a pre-interpreted output.

[083]   In another embodiment, a system uses a narrow-band light source such as a laser source similar to that shown in FIG 1B, but without the use of an interferometer. In one embodiment the laser source **110** has built-in pulse-duration and power-level controls. By suitable design, one can customize the choice of power delivered, pulse duration, frequency, and even the width of the beam. Similarly, light is delivered to a precise location via the source fiber **150** inside the catheter **200**.

Core Instrumentation

[084]   The present invention can be performed on a system using a bright light source **110** that acts as a coherent light source and emits photons in the mid-infrared range of the electromagnetic spectrum. The source can be broad-band or narrow-band, and preferably to be at least 100 times brighter than a conventional thermal source for infrared spectroscopy.

The light source may be a synchrotron radiation-based source, a free electron laser (FEL), a

laser, or other sources, preferably but not limited to one that can act as a coherent light source.

As used herein, the term, "bright" indicates that the light source provides a higher flux of

photons than the conventional thermal light source. FIG. 2 compares the flux of photons from

a bright synchrotron radiation-based source and the conventional thermal source.

[085]   In another embodiment, a controller is used to maintain optimal performance

of the source. In yet another embodiment, the source is separated and separately controlled

from the tuning system. In another embodiment, the source is coupled to a spectrophotometer,

preferably an FTIR spectrophotometer, for calibration purposes.

[086]   Suitable mid-IR sources that may be used include but are not limited to free-

electron lasers (FEL), DFG (Difference Frequency Generation) sources, tunable mid-IR diode

lasers (e.g., Pb-salt diode lasers, quantum cascade lasers), gas or chemical lasers, rare-earth-

ion lasers, solid state lasers by transitional metal doped II – VI compounds, or the SDL TC40

IR fibre laser, or thermal emission elements, or other sources that can deliver

continuous/broadband infrared light over suitable mid-range IR wavelengths. In some

embodiments, wherein the source is tunable, the source 110 can include a tuning system. In

one embodiment, where the mid-IR wavelength region chosen is longer than 3 microns,

suitable types of tunable diode lasers that may be used, include quantum cascade lasers

(QCLs) which operate at or near room temperature, and lead-salt lasers (Pb-salt) which require

operation at cryogenic temperature.

[087]   An alternative light source is a synchrotron source. Such an IR light source

was used in the experiments described below. The synchrotron beam line 1.4.3 at the

Lawrence Berkeley National Laboratory (LBNL) Advanced Light Source (ALS) was used

because it delivers coherent IR radiation with a brightness in the range of approximately 10^{11}

to 7×10^{12} photons/sec-mm2 mrad-0.1%BW over different wavelengths, which is 100-1000

times brighter than the conventional thermal source employed in regular MIR spectroscopy.

[088]   In a preferred embodiment, any source 110 used in the present apparatus

should be capable of directing light through a source fiber or optical probe 150 to an area of

tissue at a specified location 140, thereby producing a signal with sufficient signal to noise

ratio. A sufficient signal-to-noise ratio would be 3 or higher, more preferably 10 and higher, at a small area or spot size. In a preferred embodiment, the area of tissue can be from one to several μm^2 to several hundred μm^2 in size, or an area smaller or larger than the typical diameter of a mammalian cell. For example, the area of tissue can range from 1 μm^2 to 100 μm^2 up to10 cm^2.

[089]   To take advantage of minimum scattering and autofluorescence in biological tissues, several measures can be taken. In one embodiment, the source **110** can be coupled together with an appropriate detector **120**, a detection fiber **160** and source fiber **150** with minimum dispersion at the selected wavenumbers. The source fiber **150** is used to carry light from the optical source **110** to the vascular interrogation site and the detection fiber **160** carries reflectance light back to the detector **120**. In another embodiment, it is contemplated that the catheter has multiple source fibers **150** and multiple detection fibers **160** to interrogate a tissue at multiple wavenumbers in successive or simultaneous timepoints.

[090]   In a preferred embodiment, the detection fiber **160** and detector **120** in the light carrying catheter may be a single or array of detection fibers and a single or array of detectors. In one embodiment, the fiber is a fiber optic cable, for example, C1 Chalcogenide for mid-infrared 2 - 11 microns, C3 Chalcogenide for mid-infrared 2 – 6 microns, or Silver Halide for mid-infrared 4 – 18 microns or fiber optic cable coated with reflective molecules or the like.

[091]   The detection fiber **160** in the optical probe may comprise about 21 to 46 fibers. Those having skill in the art will recognize that the number of fiber arrays may be more or less, and that the length and total diameter of the probe, and the types of detection fibers may change according to teachings in the art. In another embodiment, the probe and detectors used in the catheter are those as described in Utzinger, et al, in U.S. Patent No. 6,571,118, which is hereby incorporated by reference in its entirety.

[092]   In one embodiment, the detector **120** or probe has a tip **180** comprising a focal-plane array, a mid-IR chemical camera, or an attenuated total reflection (ATR) tip, or combinations thereof. An example of a detector tip array is shown in the detail in FIG. 1B. The probe will provide chemical-imaging information. If the detector tip **180** is an ATR tip, at

least one signal beam should be introduced into an IR transparent crystal in such a way that it is incident on the internal surface at an angle which is below the critical angle, leading to total internal reflection. The geometry is set up so that many reflections or "bounces" occur before the beam exits the crystal. At each bounce an evanescent wave penetrates the medium surrounding the crystal and thereby samples the spectrum of the medium (or cell) adjacent the crystal. In a preferred embodiment, the ATR tip used is DuraDisk produced by SENSIR, which was used in the present examples.

[093]   In another embodiment, detector performance will be better increased by thermoelectric (TE) cooling or by the use of an immersion lens or both. Additionally, an LN$_2$ cooled photovoltaic or photoconductive mercury cadmium telluride (MCT) (HgCdTe) detector can be used. For example, the infrared detectors for 1.5 to 12 microns can be quantum or thermal infrared detectors whose sensitive wavelength begins in the visible or within around 1 μm to 10 or more microns of the longest wavelength, which can be increased by TE cooling. In one embodiment, the system may have DC-coupled preamps for photovoltaic detectors or AC-coupled preamps for photovoltaic or photoconductive detectors to generate customized bandwidth or special gain for the preamp.

[094]   In another embodiment, detector performance can be increased by converting the reflectance signal at the distal end of the catheter or at or near the tip 180 using a transducer system as is known in the art. By placing a transducer system at the distal end of the catheter and converting the optical signals to electrical signal can prevent weak signals from being lost. This electrical signal can be further amplified by the transducer system.

[095]   .   Referring again to FIG. 1B, the reflected IR spectrum is generated by a computer means 130. The light that the sample reflects or transmits is collected by the detectors 120, and then processed by a computer means 130. In one embodiment, the computer means 130 is also preferably a controller device which can also control, sense and record data collection of the catheter. In another embodiment, the computer means 130 can also control fiber movements of the catheter 200 and the tip 180 within the subject.

[096]   In one embodiment, the reflectance collected by the detectors 120 is processed by the computer means 190 via a Fourier transform to produce an infrared spectrum. The

computer means **190** should also be capable of analyzing and comparing the reflectance

generated spectrum as described above. In another embodiment, the comparison between the

reference spectrum and the reflected IR spectrum is carried out by software on the computer.

Having stored reference numbers allows the device to generate a pre-interpreted output. In a

preferred embodiment, the computer means **190** should contain at least the reference

wavenumbers described in Table 1 for comparison and analysis. Commercially available

software can also be used by the computer means **190** to analyze the reflectance generated

spectrum including but not limited to, CYTOSPEC (Cytospec, Inc., Croton-on-Hudson, NY),

OMNIC Spectroscopy Software Suite (Thermo Electron Corporation, Waltham, MA),

ORIGIN (Northampton, MA), and ImageProsoftware.

[097]   Each individual component is known separately in the art. Thus it is

contemplated that each component may be varied by use of the teachings of the present

invention and what is known or available in the art. For example, it is contemplated that

components described in the apparatus described as in Rava et al., in U.S. Patent No.

6,697,665, which is hereby incorporated by reference, may be used in the present invention.

<u>Alternative FTIR Instrumentation</u>

[098]   In another embodiment, after the computer generates the reflectance generated

IR spectrum, the reflectance IR spectrum is compared with a reference spectrum generated in

the interferometer **112**.

[099]   Mid-infrared reflectance generated absorption spectra are obtained by

detecting changes in infrared intensity as a function of frequency over the mid-IR molecular

fingerprint region of the electromagnetic spectrum. Most commercial instruments accomplish

this by using either dispersive or Fourier transform infrared (FTIR) spectrometers to separate

and measure infrared radiation. One can use Fourier transform infrared (FTIR) or diffusive

reflectance spectroscopy of biological systems to measure the interaction of infrared light with

biomolecules. The fundamental measurement obtained is a spectrum of infrared reflectance

(associated with energies that are not absorbed) and may be expressed as absorbance in the

sample as a function of the wavelength of IR light (typically expressed in units of

wavenumbers, cm^{-1}). Atoms inside the sample vibrate with characteristic frequencies

governed by their chemical bonding environment and as such the measured frequencies of these vibrations (the sample absorbs infrared light when the frequency of the light exactly matches the frequency of the vibration) are unique for every molecular configuration.

[0100]   FTIR spectroscopy is therefore sensitive to the presence of chemical functional groups (a structural fragment) in a molecule within biological samples. With appropriate interpretation of measured FTIR spectra one can detect, identify, and quantify many molecular species within a biological sample. This FTIR spectroscopy capability has recently been combined with microscopy, which allows one to conduct chemical analysis and map the distribution of chemical species with fine spatial resolution.

[0101]   Dispersive spectrometers use a monochromator to "single out" a particular wavelength/energy from a broad energy distribution of photons, whereas FTIR replaces the monochromator with an interferometer and collects all wavelengths simultaneously. This results in a substantially higher signal-to-noise ratio (SNR), and has greatly extended the capabilities of infrared spectroscopy and has been applied to many areas that are very difficult to analyze by dispersive instruments.

[0102]   IR radiation from a broadband source is first directed into an interferometer, where it is divided and then recombined after the split beams travel different optical paths to generate constructive and destructive interference. Next, the resulting beam passes through the sample compartment to reach to the detector. The intensity of radiation reaching the detector varies in a sinusoidal manner to produce an interferogram output. The interferogram is the record of the interference signal. If the sample happens to absorb at this frequency, the amplitude of the sinusoidal wave is reduced by an amount proportional to the amount of sample in the beam.

[0103]   The interferogram contains information over the entire mid-IR region to which the detector is responsive. Employing Fourier transformation converts the interferogram (a time domain spectrum displaying intensity versus time within the mirror scan) to the final IR spectrum, which is the frequency domain spectrum showing intensity versus frequency.

[0104]   The detector signal is sampled at small, precise intervals. The sampling rate is controlled by an internal, independent reference, a modulated monochromatic beam from a laser focused on a separate detector.

[0105]   Examples of an interferometer that may be used in the apparatus herein described is an IR Spectrophotometer such as the Nicolet Magna 760 with Nic-Plan IR Microscope, or the ThermoNicolet Nexus 870. Interferometers are generally used when observing over a broad spectrum of data, such as when a synchrotron is the source. The mid-infrared sources used in conventional FTIR instruments are thermal emission elements that produce a graybody spectrum from a filament heated to 1000 to 2000 K. These elements are physically large (at least several millimeters), and typically radiate in all directions. The optics of the FTIR bench collect and collimate the light, pass it through the scanning interferometer, and then on to the all-reflecting IR microscope where the modulated IR light is focused to a small spot on a sample. Finally, the light that the sample reflects or transmits is collected, focused onto an appropriate infrared detector, and processed by a computer via a Fourier transform to produce an infrared spectrum.

[0106]   In another embodiment, where the IR source is a synchrotron, the working of synchrotron infrared reflectance (SIR) spectromicroscopy is very similar to any conventional FTIR spectromicroscopy workstation, except for its photon source. The high brightness of synchrotron IR ("SIR") spectromicroscopy facilities capable of generating a signal to noise ratio several orders of magnitude greater than thermal IR sources for small samples (FIG. 2), enables a multitude of new scientific applications. For the study described in the Examples using SIR, a minimum signal to noise ratio of at least 20:1 is required for a spot size of 10 micron (in diameter).

[0107]   The present method and apparatus is not limited to use with a synchrotron IR source. Other IR sources which deliver the required signal to noise ratio may be used, such as DFG (Difference Frequency Generation), and/or tunable mid-IR diode lasers (e.g., Pb-salt diode lasers, quantum cascade lasers), or gas & chemical lasers, or rare-earth-ion lasers, or solid state lasers by transitional metal doped II – VI compounds, or the SDL TC40 IR fibre lasers, or other sources.

[0108]   In spite of the high brightness of SIR beam, mid-IR photons are too low in

energy (0.01 - 1.0 eV) to either break bonds or to cause ionization. It is important to use light

that does not cause ionization when introduced *in vivo*. The SIR beam has no detectable effect

on the short- and long-term viability, reproductive integrity, cell-cycle progression, and

mitochondrial metabolism in living human cells, and produces only minimal sample heating

(< 0.5°C). The SIR spectromicroscopy technique is therefore ideal for the characterizing and

studying of small and/or heterogeneous samples, for example; individual living cells,

microorganisms, and larger biological systems in which local biochemistry may have

significant spatial variations such as vulnerable plaques in aorta.

[0109]   Thus there has been described an apparatus for obtaining reflectance generated

spectrographic readings from a location within tissues of a living organism. In a preferred

embodiment, the apparatus comprises a source of broad-band mid-IR light, a computer having

a recording and/or display means, and a catheter optically coupled to the source for delivering

and returning mid-IR light and a detector having a detector tip on an end of the catheter for

placement adjacent a sample. If the source is a laser system that generates photons with a

single wavenumber or with a narrow-band mid-IR light, the apparatus would comprise a

source; a controller or the like, to maintain optimal laser performance and control the source; a

detector; and a computer. One should employ a spectrophotometer, preferably an FTIR

spectrophotometer, for calibration purposes.

[0110]   The present invention is particularly adapted for use in the diagnosis of

atherosclerotic plaques. A method for obtaining spectrographs in the mid-IR region and

interpreting these results relative to the condition of a tissue, such as an arterial wall, contacted

with the probe has been described. One or more peaks may be selected for detection and

reference, and the peaks may be represented and analyzed in a variety of ways known in the

art.

EXAMPLE 1: INTRAVASCULAR MID-IR SPECTROMICROSCOPY STUDIES OF APOE MICE

[0111]   This study characterizes specimens from apolipoprotein E (ApoE) knockout atherosclerotic mice (Francis Blankenberg, Stanford University, CA) by using intravascular mid-IR spectromicroscopy to observe the selected marker segments in the spectrograph and measure the chemical functional groups found in the specimens by reflectance generated absorbance spectroscopy. These functional groups were then related to the unique biological and chemical processes associated with the pathology of vulnerable plaques. For comparison, specimens from normal mice (Swiss) and rats (Sprague-Dawley) were treated with turpentine injection into the thigh muscle to create a model of sterile soft tissue abscesses. Results from the ApoE knockout mouse are presented in FIGs 3-6, whereas results from the mice and rats are presented in FIGs 7-10.

A. Experimental Set-up.

[0112]   All MIR spectromicroscopy measurements of the ApoE-deficient mouse aorta were carried out at the LBNL ALS. The light source used in these experiments described below is the synchrotron beam line 1.4.3 at the Lawrence Berkeley National Laboratory (LBNL) Advanced Light Source (ALS). This beam line delivers coherent IR radiation with a brightness in the range of approximately 10^{11} to 7×10^{12} photons/sec-mm2 mrad-0.1%BW over different wavelengths.

[0113]   The FTIR interferometer used in this experimental system operates as described above. Imaging experiments were also conducted using the thermal emission elements, which can be focused to as fine as 10-μm in diameter with an IR microscope and array detectors.

[0114]   To measure something smaller, such as localized biological phenomena in biological samples, one must mask away part of the incoming light, significantly reducing the signal strength. This is done by having a true point source focused to a small but not limited to diffraction-limited spot size; with 1/f optics this is approximately the half of the wavelength of the light. This is where using a synchrotron as an IR source provides advantages in the development of the present method.

[0115]   A synchrotron is a high-energy electron storage ring optimized for the production and collection of the intense light radiated by the electrons upon acceleration. For

mid-IR and longer wavelengths, the effective source size for a synchrotron light source is diffraction-limited. In other words, it is very close to an ideal point source. This means that in FTIR spectromicroscopy based on synchrotron radiation, the beam is focused to a small spot and provides several orders of magnitude greater brightness than conventional (thermal emission) IR sources. The sample can be positioned using a computer-controlled x-y-z stage with 0.1 μm precision, allowing mapping measurements of FTIR spectra as a function of x and y position on the sample.

[0116]   Synchrotron radiation from the bending magnet was collected, collimated, and transported to a commercial FTIR interferometer bench (either the Nicolet Magna 760 with Nic-Plan IR Microscope, or the ThermoNicolet Nexus 870 with Continuμm IR Microscope; both systems were N_2 purged. After modulation by the interferometer, the commercial   , infrared microscope focuses the beam onto the sample using all-reflecting optics. Biological samples were placed in an on-stage mini-incubator with environmental controls to precisely monitor temperature and moisture. The sample stage position is computer controlled with 1 micron precision. The reflected light from the sample was collected by the microscope optics and sent to the mercury-cadmium-telluride IR detector which was cooled with liquid N_2. A computer performed a Fourier transform on the measured interferogram to obtain an infrared spectrum for each sample location. The computer may also remove characteristic CO_2 peaks at 683 to 656 and 2403 to 2272 cm^{-1} and the water vapor fingerprints from the spectra.

B. Apolipoprotein E (ApoE) Mice.

[0117]   Apolipoprotein E (ApoE) is a ligand for receptors that clear remnants of chylomicrons and very low density lipoproteins. Lack of the ApoE lipoprotein causes accumulation in plasma of cholesterol-rich remnants, which accumulate in the circulation promoting atherogenesis. ApoE-deficient mice (-/-) have been generated for use as a murine model of spontaneous atherosclerosis. These knockout mice also develop gross atherosclerotic disease while on high cholesterol diets. This model is also advantageous as mice develop all phases of lesions found in humans in a time-dependent manner. Foam cell-rich deposition is usually noted by the age of 3 months followed by severe occlusion with repeated intramural

plaque hemorrhages, particularly within the brachiocephalic vessels, by the age of 8 months

with a 50% incidence of sudden death 28 weeks after initiation of a high fat/cholesterol diet.

[0118]   Swiss mice and ApoE -/- mice are recognized as an appropriate model for

human atherosclerosis. (See, for example, Journal of Lipid Research Fol. 39, 354-368, Feb.

1998, "Radical-induced lipoprotein and plasma lipid oxidation in normal and apolipoprotein E

gene knockout (ApoE -/-)mice: ApoE-/- mouse as a model for testing the role of tocopherol

mediated peroxidation in atherogenesis." See also, "Introduction of human apolipoprotein E4

"domain interaction" into mouse apolipoprotein E", *PNAS*, September 25, 2001 98(20):11587-

11591). The IR results from mice are readily transferable to human tissue, since the

phenotypic expression of atherosclerotic disease in the mouse and human tissues are .

comparable.

[0119]   ApoE -/- mice (8-13 months old) were placed on a high fat/cholesterol (1-2%)

diet for 3 months. These animals were then sacrificed and their aorta harvested.

C. Mid-IR reflectance generated absorption spectromicroscopy identification of localized

vulnerable plaques in ApoE-deficient mice (-/-) aorta

[0120]   The aorta section to be studied was placed inside the sample holder of the

mini-incubator so that the temperature and moisture were held constant during measurement

process. Optical microscope images were used as a guide to select areas with potentially

interesting information. For example, from the optical microscope images, potential sampling

locations with plaque-like materials were identified (FIG. 5).

[0121]   All infrared spectra from the selected sampling locations of the ApoE-

deficient mouse (-/-) aorta were recorded in the standard reflectance mode in the 4,000 to 650

cm^{-1} region, as this region contains unique molecular absorption fingerprints for the chemical

functional groups representative of the various pathophysiological stages of atherosclerosis.

Every IR measurement consisting of at least 2 co-added spectra at a spectral resolution

between 1 to 32 cm^{-1}, is compared by ratio to a reference spectrum similarly collected from

the most nearby area of the surface that is free of interfering molecules. The comparison was

carried out using Equation (II). Any residual water-vapor features remaining in the resultant

spectrum was removed by subtracting an appropriate scaled water-vapor spectrum. Liquid

water subtraction can be performed whenever necessary. This however, was not necessary in the experiments described herein.

D. SR-FTIR spectra of the ApoE mouse aorta

[0122]   Reflectance spectra obtained from different locations of the aorta samples of the ApoE-deficient mouse showed extreme spatial heterogeneities. In areas free of plaque-like materials (dark color of FIG. 5B), the MIR spectral signals were "silent" at the level of soft tissue background illustrated in FIG. 3, discussed below.

[0123]   .   FIG. 5A is a triple tracer autoradiograph and a visible light photograph of the same atherosclerotic mouse aorta. These images illustrate the correlation between the results of the present method and other radionuclide contrast agent-based imaging techniques. Aortic autoradiographs obtained after co-injection of annexin-Tc99m (a marker of apoptosis), FDG-F18 (a marker of metabolic activity) and MCP-1-I-125 (a marker of monocytes and macrophages) one hour after tail vein injection showed selective localization with regions of atherosclerotic plaque. One area of the aorta (taken from the apoE knockout mouse), illustrated by a box 31 in FIG. 5A and magnified in FIG. 5B, was studied both microscopically and with the present MIR technique.

[0124]   As can be seen in FIG. 5B, the area of box 31 is heterogeneous, containing both atherosclerotic and non atherosclerotic regions. The numbers 1 through 12 indicate different sampling points in this region. Each sample covers a 10 micrometer spot. The scale bar is 50 micrometers. Mid-IR spectral signals from these sampling points indicate that vulnerable plaques are a highly localized phenomenon. FIG. 6 illustrates the Mid-IR spectrograph from points 12 (6A) and 13 (6B); FIG. 7 illustrates the Mid-IR spectrograph from points 2, 4, 6 and 7; and FIG. 8 illustrates the Mid-IR spectrograph from points 8, 9, 10 and 11.

[0125]   Referring now to FIG. 4, there are shown four different tracings, offset on the y axis for clarity. The top tracing represents aorta tissue without vulnerable plaque. It was obtained a section of the ApoE-deficient mouse (-/-) aorta that lacked vulnerable plaque. The next tracing below represents vulnerable plaque (*i.e,*. plaque subject to rupture, containing lipid droplets, macrophages and apoptotic cells). These tracings are discussed in detail in

connection with FIGs. 6 and 7. Below that is a tracing obtained from a scan of lipid droplets, indicating those characteristic peaks, and at the bottom is a tracing obtained from inflamed macrophages in a non-atherosclerotic model (*i.e.* the turpentine model). Peak "h" in the bottom tracing indicates the presence of an acidic (highly protonated) environment associated with a highly active macrophage "dissolving" the turpentine-injured tissues. The first region illustrated is the C-H bond region, in the vicinity of wavenumbers 3000-2800. Peaks **a**, **b**, **c** and **d** are indicated in FIGs. 7 and 8.

[0126]   The wavenumbers for the peaks are as follows. Note that the wavenumbers are approximate, and the actual peak value may be at least 15 wavenumbers above or below the denoted peak value.

a: ~ 3007 cm^{-1}

b : ~ 2950 cm^{-1}

c : ~ 2916 cm^{-1}

d : ~ 2852 cm^{-1}

e : ~ 1743 cm^{-1}

f : ~ 1739 cm^{-1}

g: ~ 1740 cm^{-1}

h : ~ 1725 cm^{-1}

i : ~ 1678 and 1620 cm^{-1}

j: ~ 1467 cm^{-1}

k : ~ 1090, 1052, and 965 cm^{-1}

[0127]   As can be seen in FIG. 4, the spectra in Trace A taken in the C-H region, *i.e.* wavenumbers 3000-2800, in normal tissue is relatively flat, while in vulnerable plaques, peaks **a**, **b**, **c**, and **d** in the same region are readily determined in Trace B. Peaks **c** and **d** may be seen in lipid droplets (Trace C); peaks **b**, **c**, and **d** may be seen in inflamed macrophages (Trace D). The unique spectral markers within the 3600-2800 cm^{-1} region and the 1750-1500 cm^{-1} region are also visible in the Figure.

[0128]   Referring now to FIG. 6, a spectrogram of reflectance vs. wavenumber is shown for tracings 12 and 13. By comparing these tracings to FIG. 4, it can be seen that these spots represent normal arterial wall. FIG. 6 is characterized by broad featureless peaks in the vicinities of 2800 to 3400 and 1700 to 1000, similar to the top tracing in FIG. 4. The absorbance in normal tissue has values often exceeding 2 units, which is generally considered as spectroscopically "silent". This is because of the high absorption of infrared photons by the cardiac-muscle cells, which is expected from our experience. The overall spectral pattern and the simultaneous presence of amide I (~1648 cm^{-1}) and amide II (~1548 cm^{-1}) peaks recorded at location #13 indicate the possible presence of non-cardiac-muscle cells.

[0129]   In FIG. 7, tracings 2, 4, 6 and 7 are shown. These four tracings are from spots in FIG. 3B that show atherosclerotic plaque. One may observe the characteristic sharp peaks at **a, b, c and d** as described in FIG. 4. FIG. 7 also shows a series of peaks **e, i, j, and k** that that are either higher or differently shaped in the region of vulnerable plaques. Note that some blood apparently has interfered with the reading of spot 6, as indicated by peak **i** characteristic of protein. Peak **i** in this case is equal in height to the adjacent peak.

[0130]   In FIG. 8, tracings 8, 9, 10, and 11 are shown. These spots are also from plaques that are vulnerable. The tracings can again be seen to be consistent with the characteristics pointed out above. Again there are distinct peaks in the region 3000 to 2800 and 1800 to 1600. In spot 8 (top line), the trailing upward towards the lower wavenumber 1000 is considered indicative of a necrotic cell (rather than an apoptotic cell).

EXAMPLE 2: INTRAVASCULAR MID-IR SPECTROMICROSCOPY RABBIT STUDIES PERFORMED IN VIVO AND EX VIVO

[0131]   Retired female breeder Watanabe heritable hyperlipidemic (WHHL) rabbits (Covance Research Laboratories, Princeton, New Jersey) greater than 12 months in age are placed on a high fat/cholesterol (2%) diet for 0 or 3 months (Certified Rabbit Diet 5322, LabChows®, Purina Mills, Inc.). 5 animals per time point are studied.

[0132]   An apparatus shown schematically in FIG. 1B can be used to generate intravascular mid-infrared reflectance generated absorption spectra by detecting changes in

infrared intensity as a function of frequency over the mid-IR molecular fingerprint region of

the electromagnetic spectrum. A mid-IR light source is connected to a detector having a

controller, and to a computer which also serves as an output controller and/or processing

means. The IR light source also can be optically connected to a Fourier transform infrared

(FTIR) or diffusive reflectance spectroscopy interferometer.

[0133]   A 5 French catheter sheath will be connected to the detectors and the source.

The catheter is comprised of a detection fiber and a source fiber, having a detector tip. The

catheter is inserted into the lumen of a rabbit artery or other tissues suspected of containing

physiological markers indicative of vascular disease or other inflammatory conditions.

[0134]   Each animal will undergo intra-arterial catheterization with a 5 French catheter

sheath through of a femoral artery through which the mid-IR catheter will be placed into the

root of the aorta. The mid-IR catheter will then be precisely rotated and withdrawn in spiral

mode to acquire a mid-IR spectral map of the thoracic and abdominal aorta. The source emits

a signal that is transmitted through the source fiber and emitted at the intravascular

interrogation site. The detector tip detects the reflectance generated light after it has been

reflected and absorbed by the surrounding tissues and transmits the signal through the

detection fiber to the computer.

[0135]   The animal will then be sacrificed and the thoracic and abdominal aorta with

their side braches will be carefully dissected, removed, incised longitudinally along the

anterior long axis of the aorta and layed out flat mounting media for ex vivo mid-IR and

histologic analyses at LBNL. The in vivo mid-IR spectral map can be reformatted and

flattened out into a 2 dimensional format oriented in the same fashion as the incised aorta. The

2 dimensional mid-IR spectra from the *in vivo* and *ex vivo* IMIR studies will then be directly

and systematically compared digitally in order to determine the *in vivo* sensitivity and

resolution of the mid-IR catheter and its correlation with the histologic and biochemical

features of atherosclerotic plaques.

[0136]   The ability of the mid-IR catheter of FIG. 1B and FIG. 1C to detect decreases

in the severity of atherosclerotic plaques in response to statin cholesterol lowering therapy can

be assessed *in vivo*. In two separate groups of animals after the period of high fat/cholesterol

diet and the drawing of serum triglyceride and cholesterol levels animals are placed on a

normal diet and receive one month of statin therapy with atorvastatin, 20 mg/kg/day in

drinking water according to a modification of the model of Weis et al., "Statins have biphasic

effects on Angiogenesis," *Circulation* 2002;105:739-745. Animals will then have repeat

triglyceride and cholesterol levels drawn and are imaged with the mid-IR catheter *in vivo* and

ex vivo in the same manner as untreated rabbits as described above.

EXAMPLE 3: EX SITU ANIMAL AND HUMAN TISSUE STUDIES USING IMIR

[0137]   Rabbit and human tissues from normal and atherosclerotic aortas supplied by a

cardiologist are analyzed as described in the previous Examples. In addition, the apparatus

described in Example 2 and shown in FIG. 1B is used with a Continuμm XL FT-IR imaging

microscope (Nicolet Thermo-electron corporation) which is equipped with both infrared and

ATR objectives. The apparatus is used to image mid-infrared spectra of aorta specimens from

rabbits and humans. Infrared spectral signatures from different types of plaques, such as thick

plaques, plaques with grossly intact endothelial surface, etc., will be interrogated using the

methods as described in Examples 1 and 2. The rabbit tissues are similar to the tissues

described in Example 2. The human tissues are harvested arterial tissues from human patients

having vascular disease and suffered from sudden cardiac death. The pathologies of these

tissues are known. Therefore, the spectra obtained from these tissues can be readily confirmed

by a pathologist. Using the mid-IR peaks disclosed in Table 1, a diagnosis of whether the

tissues contain vulnerable plaques and at which specific locations are obtained by observing

the spectra at each location interrogated. The diagnosis should match that of the pathologist,

whose conclusion was obtained by using light microscopy. Each tissue is classified as normal

or containing vulnerable plaques using standard diagnostic criterion.

[0138]   The spectral signals obtained from tissues having plaques will be compared

with normal tissues that do not have plaques. The results then will be validated by histological

analysis.

EXAMPLE 4: CLINICAL TRIALS USING IMIR

[0139]   Reflectance spectra will measured by intravascular mid-IR spectroscopy in

volunteers with no history of coronary or aortic atherosclerotic disease at specified distinct

clinically normal sites in intravascular tissues using the apparatus similar to that described in

Example 2 and 3. The spectra taken of intravascular tissues from the normal patients will be

compared to spectra taken of patient with a known or suspected coronary and aortic

atherosclerotic disease.

[0140]   Following initial screening in a patient with a known or suspected coronary

and aortic atherosclerotic disease, reflectance spectra is measured in least 2-5 interrogation

sites. Each patient will undergo intra-arterial catheterization with a catheter sheath through a

femoral artery through which a mid-IR catheter will be placed into the root of the aorta. The

catheter may have a camera on its distal end used for visual inspection of the tissues. The mid-

IR catheter will then be precisely rotated, inserted and withdrawn, preferably in spiral mode,

to acquire a mid-IR spectral map of the thoracic and abdominal aorta. The reflectance of each

interrogation site is measured. In addition to the two to five abnormal sites, reflectance spectra

are measured from one to three neighboring normal sites. Post-spectroscopy, abnormal sites

are again probed using a catheter and known techniques such as intravascular ultrasound, to

obtain angiographic images to assess lesion and plaque morphology and severity. A clinical

diagnosis of each lesion or plaque as normal or vulnerable and recorded by an experienced

vascular pathologist. During follow up surgeries, a 2-4 mm biopsy of the tissue may be taken

from the interrogated area. These specimens are evaluated by an experienced pathologist using

light microscopy and classified as normal or containing vulnerable plaques using standard

diagnostic criterion. Biopsies with multiple diagnoses will be classified according to the most

severe pathological diagnosis. The pathologist and clinicians may be blinded to the results of

the spectroscopic analyses.

[0141]   The spectra from the normal patients and the suspected diseased patients will

be compared. Using the mid-IR peaks disclosed in Table 1, the physician should be able to

diagnose whether the suspected diseased patients have vulnerable plaques in their arteries and

at which specific locations. The diagnosis should match that of the pathologists.

[0142]   The present embodiments described herein in the examples, methods, procedures, apparatus and devices are meant to exemplify and illustrate the invention and should in no way be seen as limiting the scope of the invention. Any patents or publications mentioned in this specification are indicative of levels of those skilled in the art to which the patent pertains and are hereby incorporated by reference to the same extent as if each was specifically and individually incorporated by reference.

References for table:

Barth, A. (2000). "The infrared absorption of amino acid side chains [Review]." Progress in Biophysics & Molecular Biology 74(3-5): 141-173.

Chiriboga, L., P. Xie, et al. (1998). "Infrared Spectroscopy of Human Tissue - Ii - a Comparative Study of Spectra of Biopsies of Cervical Squamous Epithelium and of Exfoliated Cervical Cells." Biospectroscopy 4(1): 55-59.

Gaigneaux, A., J. M. Ruysschaert, et al. (2002). "Infrared spectroscopy as a tool for discrimination between sensitive and multiresistant K562 cells." European Journal of Biochemistry 269(7): 1968-1973.

Hadden, J. M., M. Bloemendal, et al. (1994). "Structure and Thermal Stability of the Extracellular Fragment of Human Transferrin Receptor at Extracellular and Endosomal Ph." FEBS Letters 350(2-3): 235-239.

Knells, G., M. K. Ahmed, et al. (1995). "Fourier-Transform Infrared Spectroscopic Analysis of Rabbit Lung Surfactant - Subfraction-Associated Phospholipid and Protein Profiles." Chemistry & Physics of Lipids 77(2): 193-201.

Lecoutre, J., L. R. Narasimhan, et al. (1997). "The Lipid Bilayer Determines Helical Tilt Angle and Function in Lactose Permease of Escherichia Coli." Proceedings of the National Academy of Sciences of the United States of America 94(19): 10167-10171.

Lewis, E. N. and R. N. McElhaney (1996). Fourier transform infrared spectroscopy in the study of hydrated lipids and lipid bilayer membranes. Infrared spectroscopy of biomolecules. New York, Wiley-Liss: 159-202.

Lewis, R., M. Kiricsi, et al. (2003). "Fourier transform infrared spectroscopic study of the interactions of a strongly antimicrobial but weakly hemolytic analogue of gramicidin S with lipid micelles and lipid bilayer membranes." Biochemistry 42(2): 440-449.

Lewis, R. and R. N. McElhaney (2000). "Calorimetric and spectroscopic studies of the thermotropic phase behavior of lipid bilayer model membranes composed of a homologous series of linear saturated phosphatidylserines." Biophysical Journal 79(4): 2043-2055.

Lewis, R., S. Tristram-Nagle, et al. (2001). "The thermotropic phase behavior of cationic lipids: calorimetric, infrared spectroscopic and X-ray diffraction studies of lipid bilayer membranes composed of 1,2-di-O-myristoyl-3-N,N,N-trimethylaminopropane (DM-TAP)." Biochimica et Biophysica Acta - Biomembranes 1510(1-2): 70-82.

Liu, K. Z., M. Jackson, et al. (1996). "Modification of the Extracellular Matrix Following Myocardial Infarction Monitored by Ftir Spectroscopy." Biochimica et Biophysica Acta - Molecular Basis of Disease 1315(2): 73-77.

Liu, K. Z. and H. H. Mantsch (2001). "Apoptosis-induced structural changes in leukemia cells identified by IR spectroscopy." Journal of Molecular Structure 565(Special Issue SI): 299-304.

Liu, K. Z., H. H. Mantsch, et al. (1996). "Infrared Spectroscopic Determination of Hepatic Nuclei Oxidation." Biospectroscopy 2(1): 39-45.

Liu, K. Z., R. A. Shaw, et al. (2002). "Reagent-free, simultaneous determination of serum cholesterol in HDL and LDL by infrared spectroscopy." Clinical Chemistry 48(3): 499-506.

Maleev, V., A. Semenov, et al. (2003). "Spectroscopic and calorimetric study of DNA interaction with a new series of actinocin derivatives." Journal of Molecular Structure 645(2-3): 145-158.

McCrae, K. C., T. Rand, et al. (2001). "Analysis of pulmonary surfactant by Fourier-transform infrared spectroscopy following exposure to Stachybotrys chartarum (atra) spores." Chemistry & Physics of Lipids 110(1): 1-10.

Mythili, J., T. P. Sastry, et al. (2000). "Preparation and characterization of a new bioinorganic composite: collagen and hydroxyapatite." Biotechnology & Applied Biochemistry 32(Part 3): 155-159.

Naumann, D., C. P. Schultz, et al. (1996). What can infrared spectroscopy tell us about the structure and composition of intact bacterial cells? Infrared spectroscopy of biomolecules. D. Chapman. New York, Wiley-Liss: 279-310.

Vyavahare, N., M. Ogle, et al. (1999). "Elastin calcification and its prevention with aluminum chloride pretreatment." American Journal of Pathology 155(3): 973-982.

Wennerberg, J., E. Kjellen, et al. (1993). "Biochemical Modulation of Chemotherapy and Radiotherapy in Head and Neck Cancer." Anticancer Research 13(6B): 2501-2506.

Hoi-Ying N. Holman, Kathleen A. Bjornstad, Morgan P. McNamara, Michael C. Martin, Wayne R. McKinney, and Eleanor A. Blakely, "Synchrotron Infrared Spectromicroscopy as a Novel Bioanalytical Microprobe for Individual Living Cells: Cytotoxicity Considerations," J. Biomedical Optics, 7(3), 417-424 (2002). And selected for the Virtual Journal of Biological Physics Research, 4(3) (2002).

Hoi-Ying N. Holman, Michael C. Martin, and Wayne R. McKinney, "Tracking chemical changes in a live cell: Biomedical Applications of SR-FTIR Spectromicroscopy,"

Proceedings of the First International Conference on Biomedical Spectroscopy, Cardiff, Wales, July 7-10, 2002. *Spectroscopy - An International Journal* **17**(2-3), 139-159 (2003).

Hoi-Ying N. Holman, Michael C. Martin, and Wayne R. McKinney, "Synchrotron-Based FTIR Spectromicroscopy: Cytotoxicity Considerations," *J. Biological Physics* **29**, 275-286 (2003).